

REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-04-

0480

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1. REPORT DATE (DD-MM-YYYY) 12-31-03		2. REPORT TYPE Final Technical Report		3. DATES COVERED (From - To) 2002-2003
Theoretical Prediction of Limit Cycle Oscillations in Support of Flight Flutter Testing				5a. CONTRACT NUMBER F49620-01-1-0148
				5b. GRANT NUMBER 313-6009
				5c. PROGRAM ELEMENT NUMBER NA
6. AUTHOR(S) Earl H. Dowell Kenneth C. Hall.				5d. PROJECT NUMBER NA
				5e. TASK NUMBER NA
				5f. WORK UNIT NUMBER NA
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)				8. PERFORMING ORGANIZATION REPORT NUMBER NA
Duke University Mech. Eng. and Materials Sciences Pratt School of Engineering P.O. Box 90300 Durham, NC 27708				
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office of Scientific Research 4015 Wilson Boulevard, Room 713 Arlington, VA 22203-1954				10. SPONSOR/MONITOR'S ACRONYM(S) AFOSR
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) NA
12. DISTRIBUTION / AVAILABILITY STATEMENT No Limitations				
13. SUPPLEMENTARY NOTES NA				
14. ABSTRACT Using a novel harmonic balance method and a state of the art computational fluid dynamics (CFD) model, limit cycle oscillations have been calculated for a conventional and supercritical airfoil as well as the F-16 wing. The latter result is the first of its kind.				
DISTRIBUTION STATEMENT A Approved for Public Release Distribution Unlimited				
15. SUBJECT TERMS Aeroelasticity, Limit Cycle Oscillations, Unsteady Aerodynamics				
16. SECURITY CLASSIFICATION OF: NA		17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 25	19a. NAME OF RESPONSIBLE PERSON Earl H. Dowell
a. REPORT NA	b. ABSTRACT NA	c. THIS PAGE NA		19b. TELEPHONE NUMBER (include area code) 919-660-5302

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FINAL TECHNICAL REPORT
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
THEORETICAL PREDICITON OF LIMIT CYCLE OSCILLATIONS IN SUPPORT OF
FLIGHT FLUTTER TESTING

AFOSR GRANT NUMBER F49620-01-1-0148

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Principal Investigator
Department of Mechanical Engineering and Materials Science
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December 31, 2003

We have done a wide-ranging parameter study for the typical section airfoil including the effects of plunge to pitch frequency ratio, mass ratio and Mach number. These calculations were done by exercising our reduced order modeling capability to obtain the many flutter points required much more rapidly than would be the case using conventional methods. This work has now been extended to the calculation of limit cycle oscillations (LCO) to show the effects of the same parameters. At the moment we are concentrating on the determination of LCO due to aerodynamic nonlinearities.

The results obtained are quite interesting and show the following effects.

- 1) There can be a change in LCO due to aerodynamic nonlinearities from benign to dangerous as the Mach number is changed. By benign LCO we mean no LCO below the nominal flutter speed and by dangerous LCO we mean LCO can occur below the nominal linear flutter speed.
- 2) Our results for LCO including viscous effects in the aerodynamic model, are being compared to experiment. Initial results are promising.
- 3) The above LCO calculations have now been extended to 3D inviscid flow. Current work is directed toward adding the effects of viscosity to the 3D flow model.

We have submitted two abstracts to the 2003 AIAA SDM conference that cover items 1-2 above and another paper is to be presented at the ASME International Congress this fall discussing Item 3.

Attached is a copy of the presentation presented at the AFOSR T&E Meeting in June 2003 summarizing our work to date. Among the most significant results are the first predictions of Limit Cycle Oscillations for the F-16 aircraft due to aerodynamic nonlinearity.

THEORETICAL PREDICTION OF LIMIT CYCLE OSCILLATIONS

**Earl Dowell
Duke University**

**AFOSR TEST AND EVALUATION PROGRAM
South Lake Tahoe, California
June 4-5, 2003**

**KEY T&E CENTER CONTACT: DR. CHARLES DENEGRI
SEEK EAGLE OFFICE, EGLIN AFB**

PROGRESS TO DATE

- DEVELOPMENT OF RAPID & ACCURATE CFD MODELS
- DETERMINATION OF FLUTTER BOUNDARIES AND LIMIT CYCLE OSCILLATIONS

- * 2D,INVISCID
- * 2D, VISCOUS
- * 3D,INVISCID
- * 3D, VISCOUS

- APPLICATIONS TO
- * SUPERCRITICAL AIRFOIL, NLR 7301
(VISCOUS)
- * AGARD WING, 445.6 (VISCOUS)
- * F-16 WING (INVISCID)

PLANS FOR NEXT YEAR

- METHODS DEVELOPMENT: EXTENSION TO WING PLUS STORES
- APPLICATIONS TO
 - * F-16 WING (VISCOUS)
 - * F-16 WING PLUS STORES (INVISCID)
 - * MAVRIC WING (INVISCID)

RESULTS TRANSITIONED TO T&E CENTER

- F-16 RESULTS
- RAPID AND ACCURATE CFD CODES
(PENDING)

PUBLICATIONS

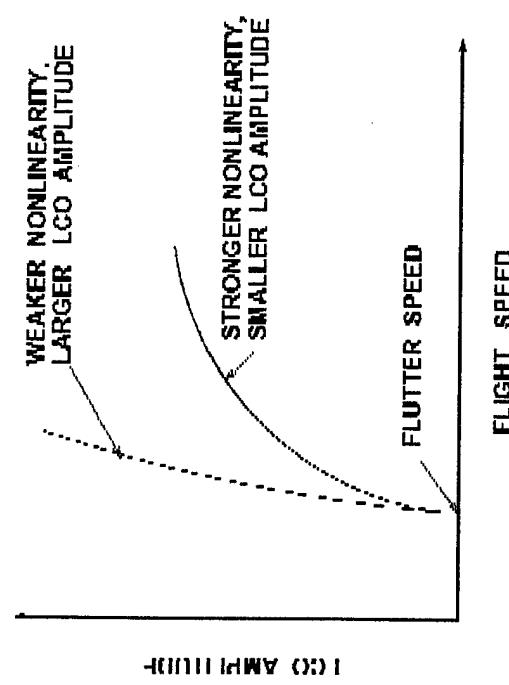
THOMAS, J. P. , DOWELL, E. H. AND HALL, K.C., "NONLINEAR INVISCID AERODYNAMIC EFFECTS ON TRANSONIC DIVERGENCE, FLUTTER AND LIMIT CYCLE OSCILLATIONS," AIAA JOURNAL, VOL. 40, NO. 4, 2002, PP. 638-646.

THOMAS, J. P. , DOWELL, E.H., AND HALL, K.C., "A HARMONIC BALANCE APPROACH FOR MODELING THREE-DIMENSIONAL NONLINEAR UNSTEADY AERODYNAMICS AND AEROELASTICITY," ASME PAPER IMECE-2002-32532, PROCEEDINGS OF THE ASME INTERNATIONAL MECHANICAL ENGINEERING CONFERENCE AND EXPOSITION, NOVEMBER 17-22, 2002, NEW ORLEANS, LA.

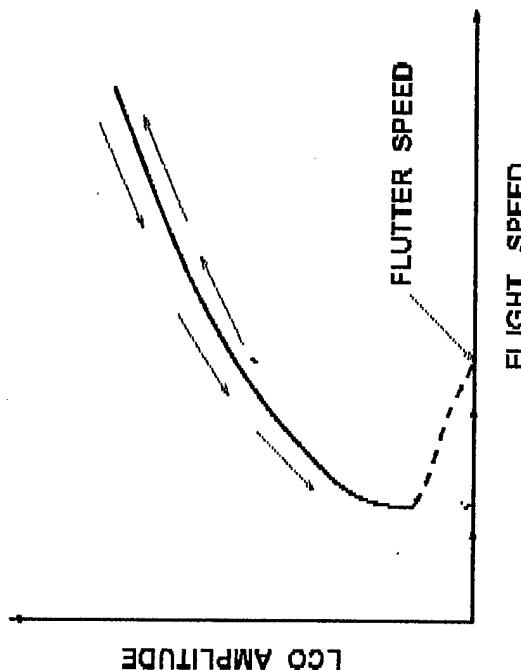
THOMAS, J. P., HALL, K. C. AND DOWELL, E. H., "A HARMONIC BALANCE APPROACH FOR MODELING NONLINEAR AEROELASTIC BEHAVIOR OF WINGS IN TRANSONIC FLOW," AIAA PAPER-2003-1924, PRESENTED AT THE 44TH AIAA/ASME/ADC/AHS/ASC STRUCTURES, STRUCTURAL DYNAMICS AND MATERIALS CONFERENCE AND EXHIBIT, APRIL 7-10, 2003, NORFOLK, VA.

SCHEMATIC OF LIMIT CYCLE OSCILLATION RESPONSE

“Good” Nonlinearity



“Bad” Nonlinearity



THE SEVERAL PHYSICAL SOURCES OF NONLINEARITIES

STRUCTURE

- CONTROL SURFACE FREE-PLAY (SUBCRITICAL & VERY STRONG)
- WING-STORE FREE-PLAY (?)
- PLATE-LIKE STIFFNESS (SUPERCRITICAL & STRONG)
- VERY HIGH ASPECT RATIO WING (SUBCRITICAL & MODERATELY STRONG)

FLUID (OUR FOCUS TODAY)

- SHOCKWAVES (SUB OR SUPERCRITICAL & WEAK USUALLY, BUT MAY BE STRONG)
- SEPARATED FLOW (SUB OR SUPERCRITICAL & STRONGER)

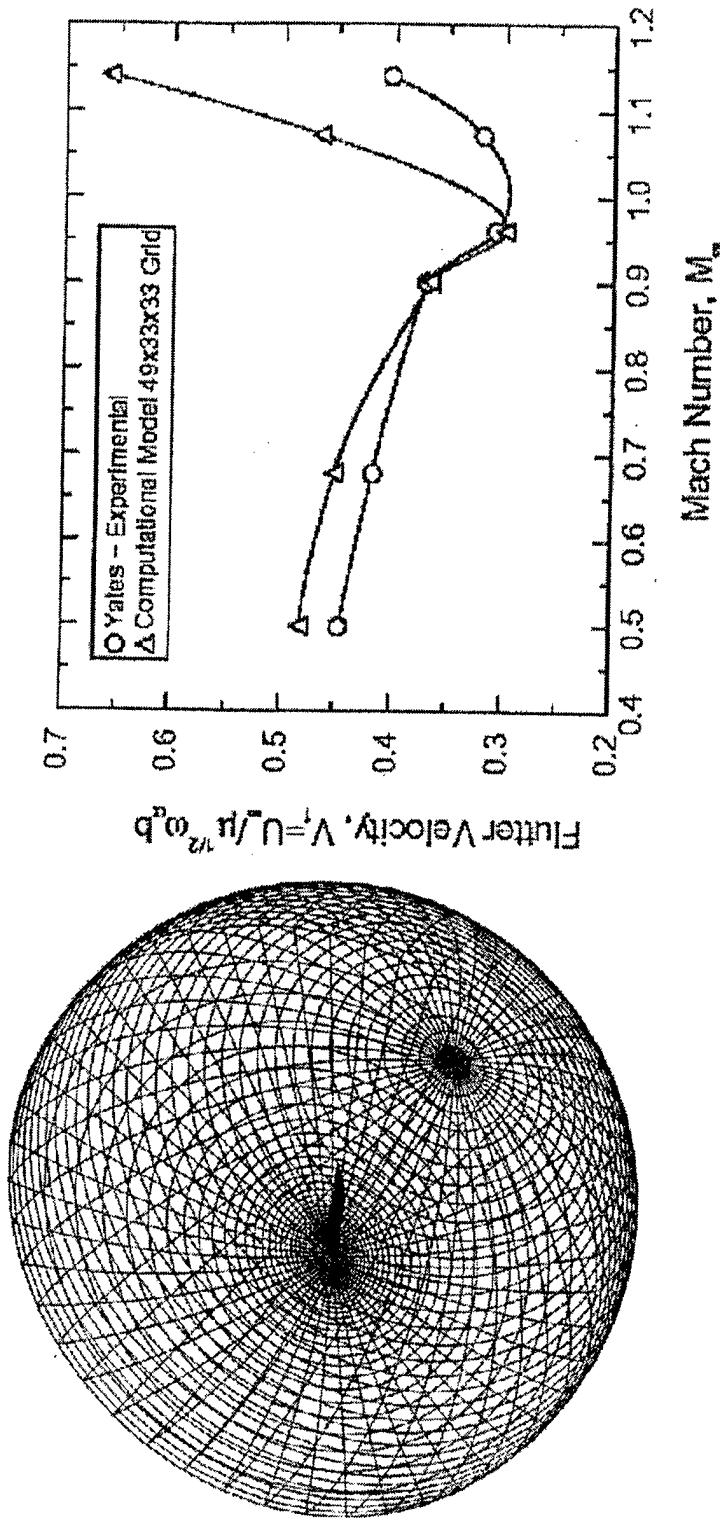
LCO DUE TO AERODYNAMIC NONLINEARITIES

- SHOCKWAVES
- SEPARATED FLOW

ACCURATE, EFFECTIVE AND EFFICIENT COMPUTATIONAL METHODS: THREE IMPORTANT IDEAS

1. FIRST DETERMINE A NONLINEAR STATIC STATE OF THE SYSTEM, THEN CONSIDER SMALL (LINEAR) DYNAMIC PERTURBATION ABOUT THAT STATIC STATE, E.G. A NONLINEAR STEADY FLOW WITH SHOCKS AND/OR FLOW SEPARATION. THE “LOCAL” (IN PHASE SPACE) SYSTEM STABILITY MAY THEN BE DETERMINED.
2. FOR A NONLINEAR, DYNAMIC MODEL EXPAND THE SOLUTION IN A FOURIER SERIES IN TIME AND RETAIN ONLY A FEW HARMONICS. THIS IS NORMALLY SUFFICIENT TO DETERMINE LIMIT CYCLE OSCILLATIONS OF FLUID-STRUCTURAL SYSTEMS.
 - COMPUTATIONAL COST OF (1) OR (2) IS COMPARABLE TO THAT OF THE NONLINEAR STATIC OR STEADY FLOW SOLUTION.
3. EXPAND SOLUTION IN TERMS OF GLOBAL MODES FOR STRUCTURE AND FLUID.
 - COMPUTATIONAL COST OF (3) IS USUALLY REDUCED BY SEVERAL ORDERS OF MAGNITUDE OVER THAT OF A SOLUTION BASED UPON A MODEL USING GENERALIZED COORDINATES ON LOCAL SPATIAL GRIDS.

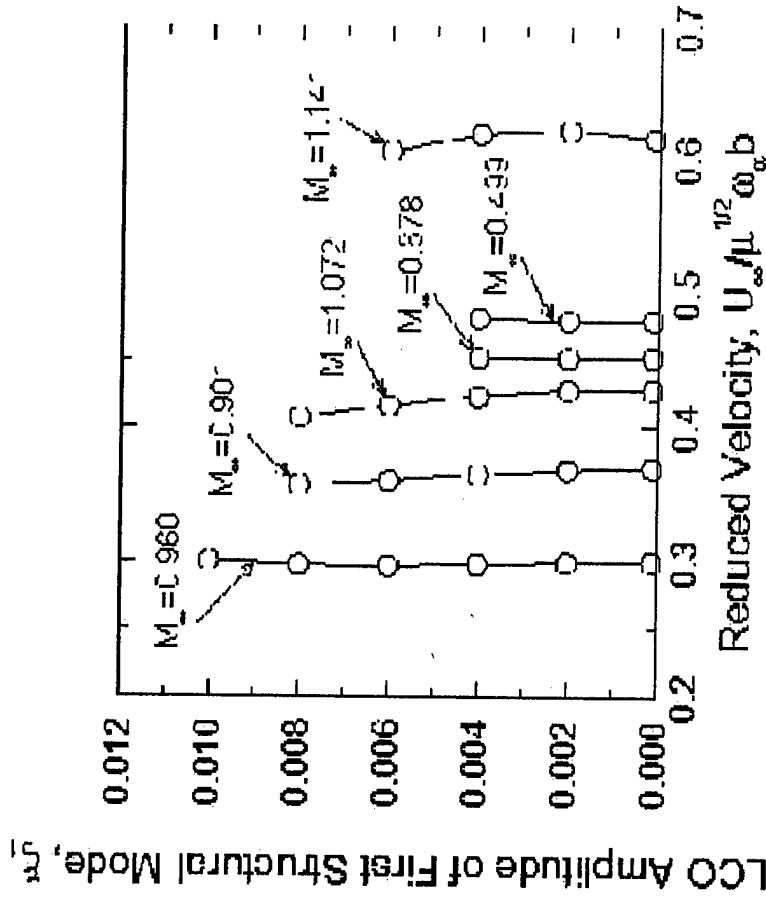
Accomplishments – New Scientific Findings HB flutter solution of a 3D AGARD 445.6 wing



Correlates well with experimental measurements at $M < 1$



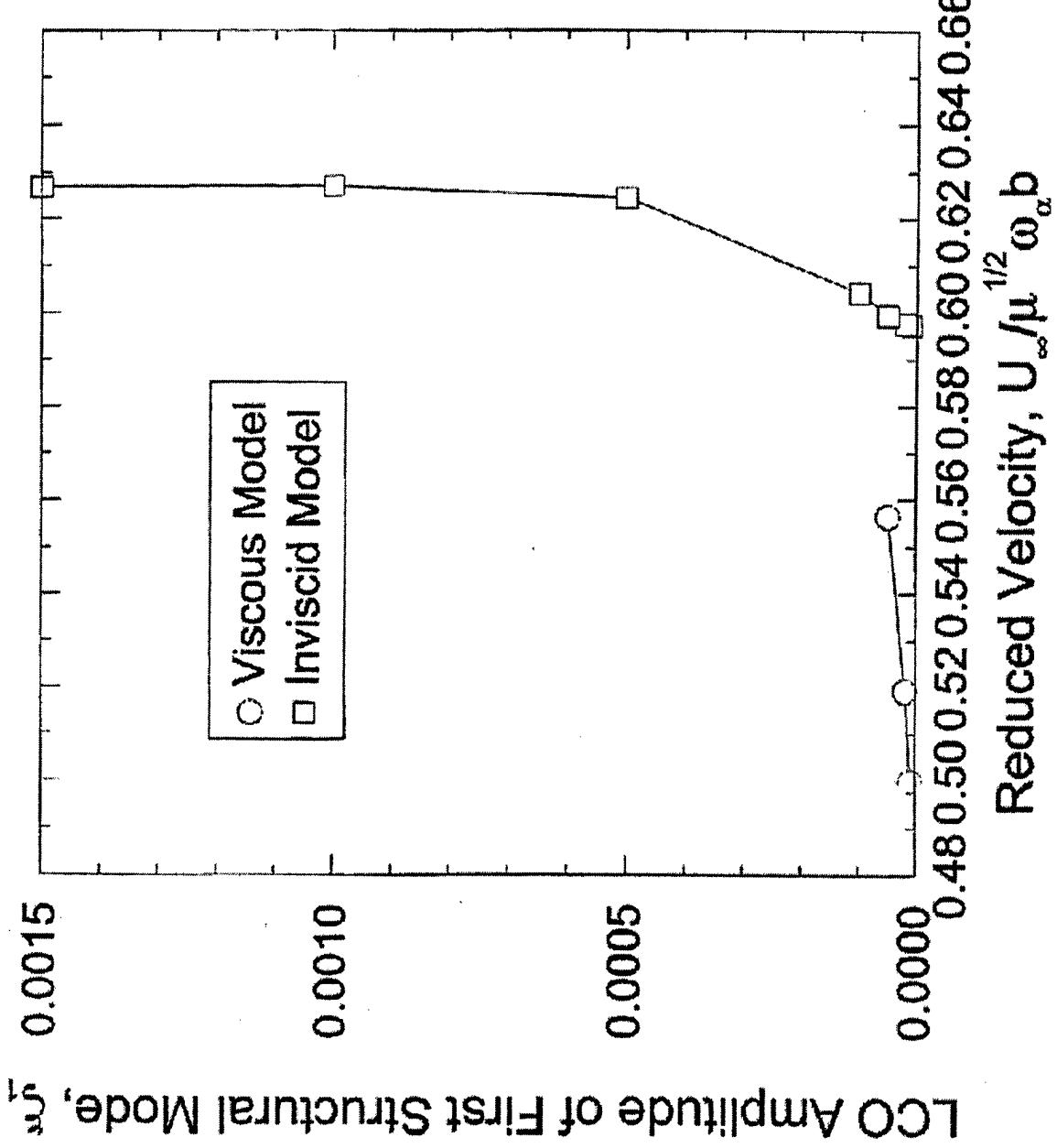
ACCOMPLISHMENTS - NEW SCIENTIFIC FINDINGS HB FLUTTER SOLUTION OF A 3D AGARD 445.6 WING



PREDICTS AN UNSTABLE LCO IN LOW SUPERSONIC MACH NUMBER RANGE. LCO OF LARGE AMPLITUDE MAY BE ENCOUNTERED BELOW THE PREDICTED FLUTTER BOUNDARY

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LCO Response Amplitude Vs. Reduced Velocity

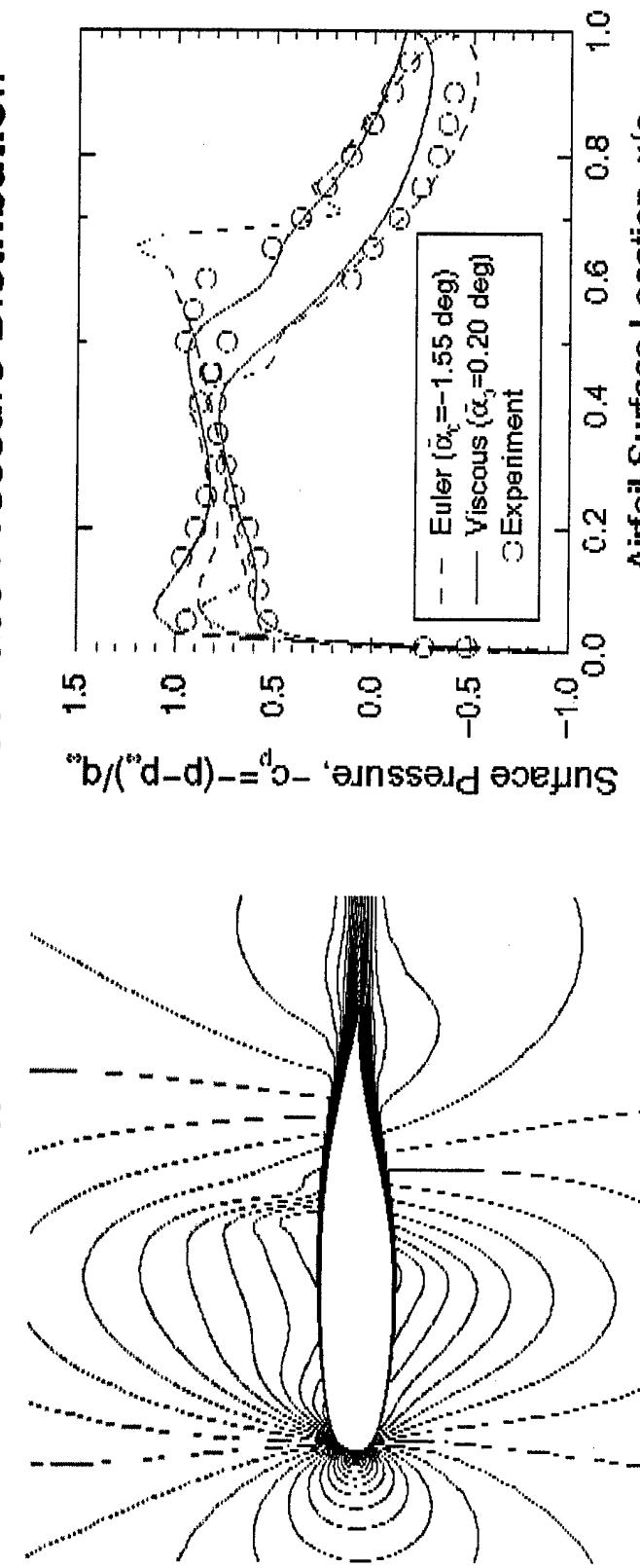


Duke University

VISCOUS TRANSONIC AIRFOIL AEROELASTIC MODEL NLR 7301 AIRFOIL SECTION

Mach Contours $M_\infty = 0.75$

Surface Pressure Distribution

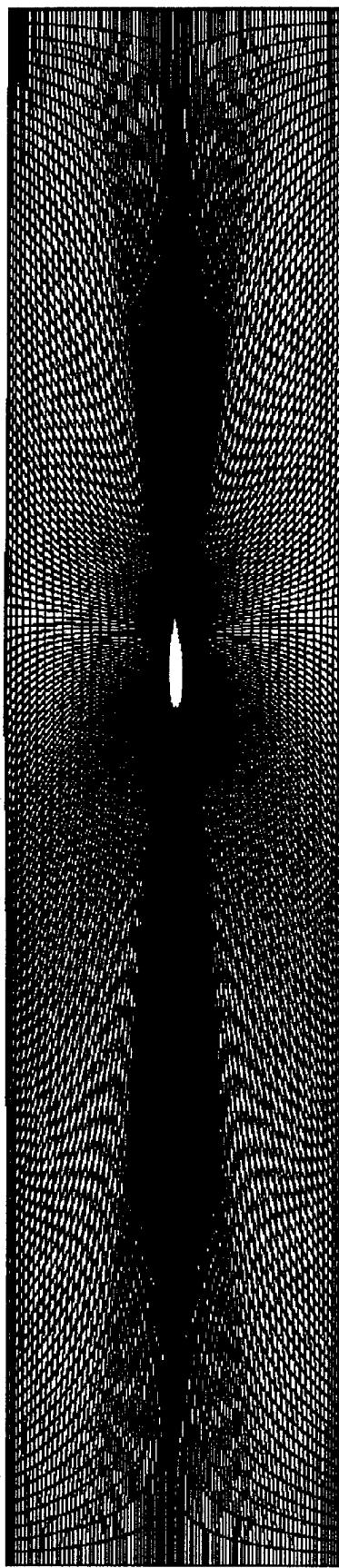


STEADY FLOW PRESSURE DISTRIBUTION: COMPARISON OF THEORIES
AND EXPERIMENT

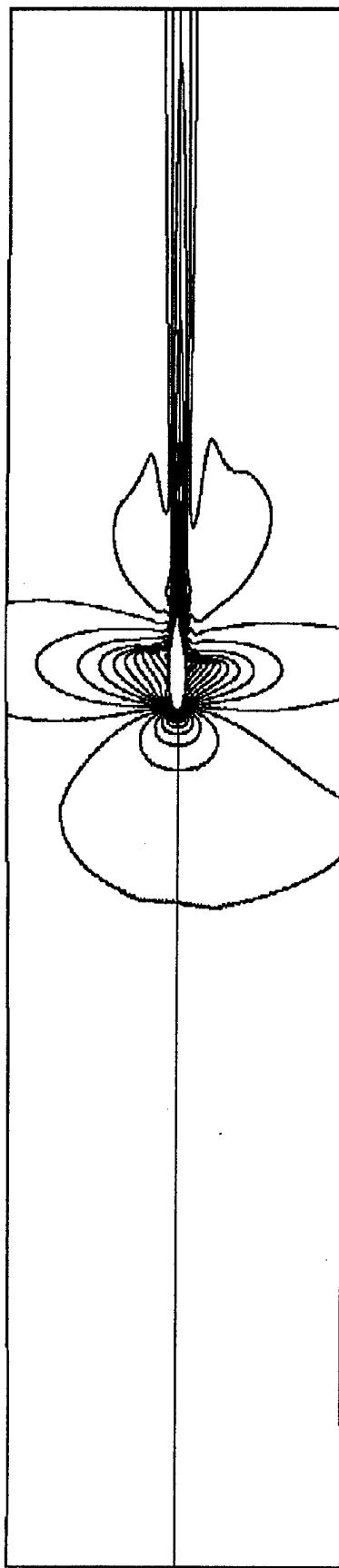
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NLR 7301 Airfoil in Wind-Tunnel Test Section Computational Mesh and Steady Mach Contours

Computational Mesh

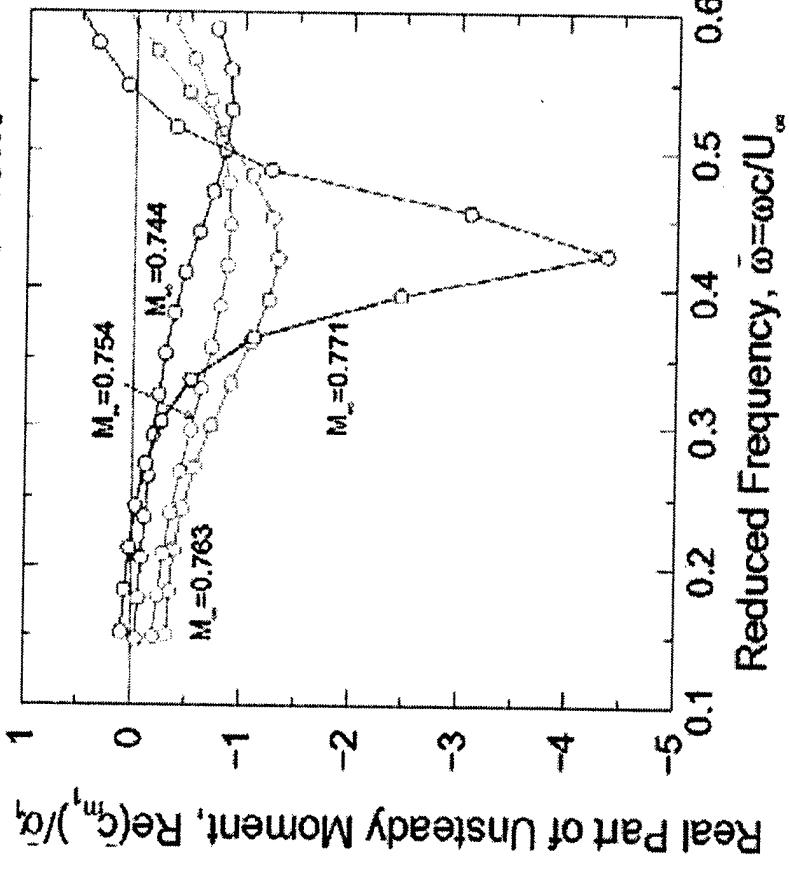


Mach Contours

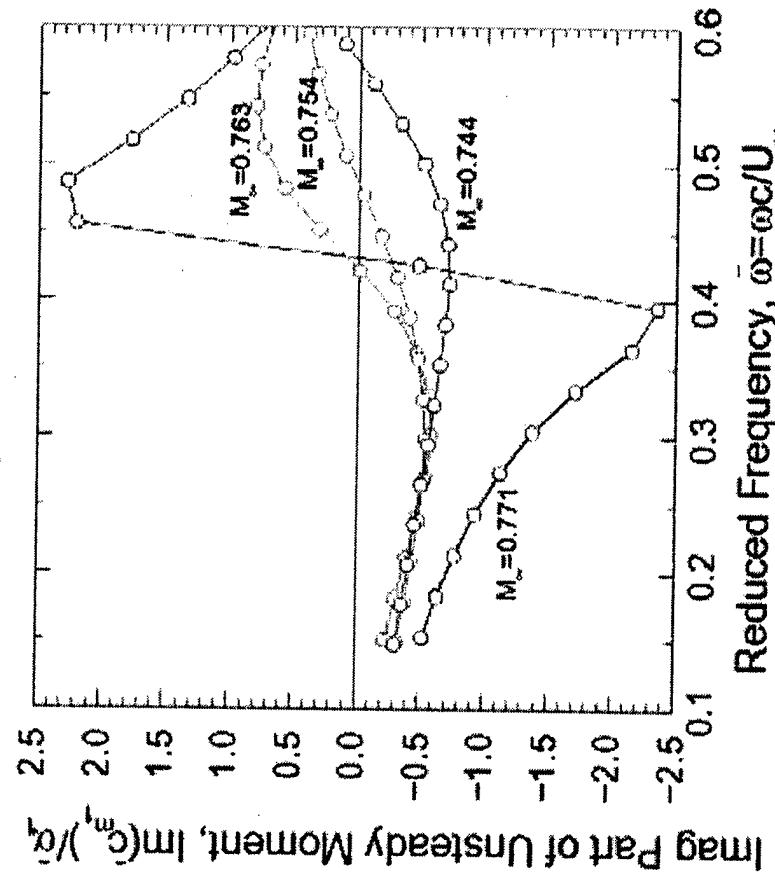


NLR 7301 Airfoil in Wind-Tunnel Test Section Computed Unsteady Moment Data

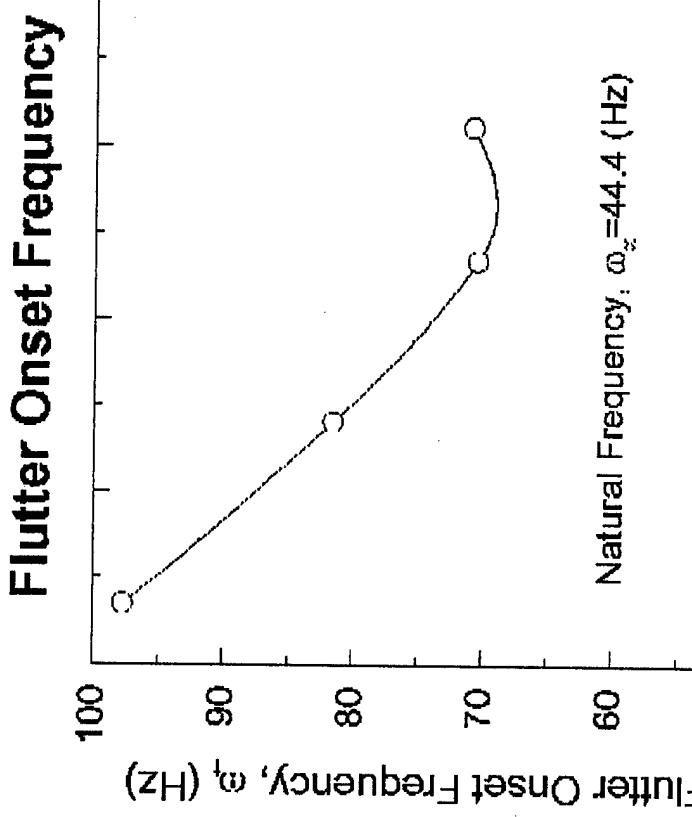
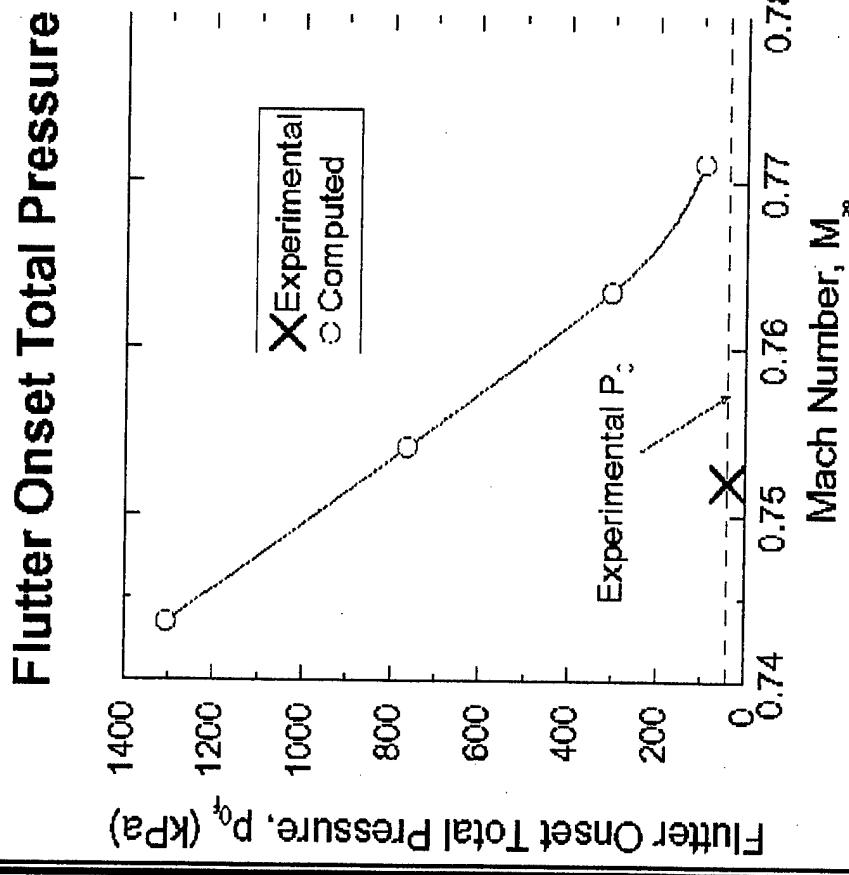
Real Part of Moment



Imaginary Part of Moment



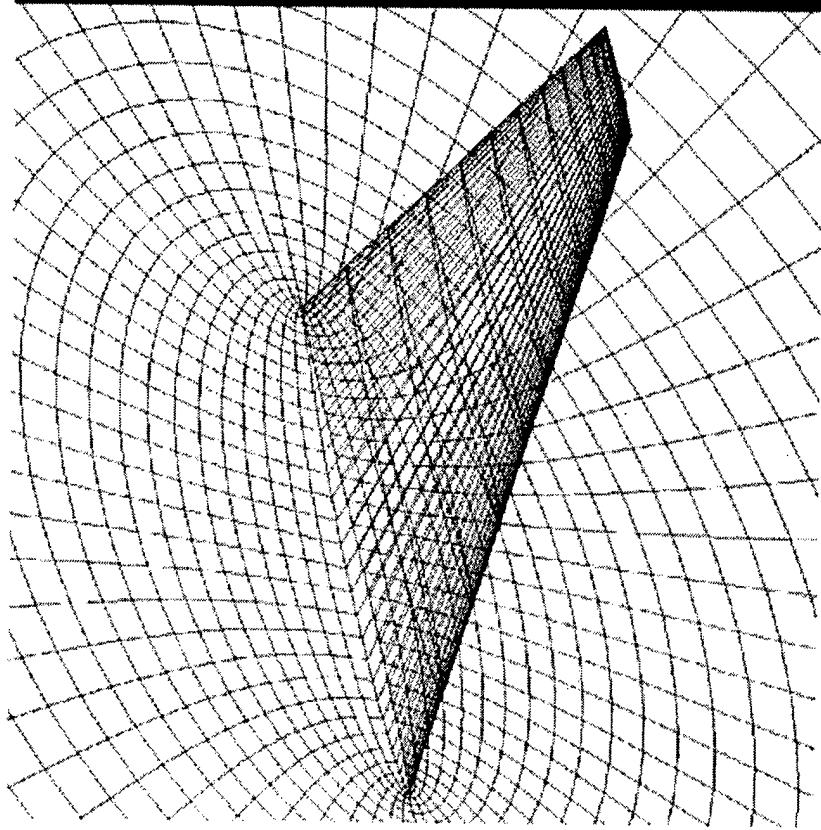
NLR 7301 Airfoil in Wind-Tunnel Test Section Calculated Single Degree-of-Freedom Flutter Trend



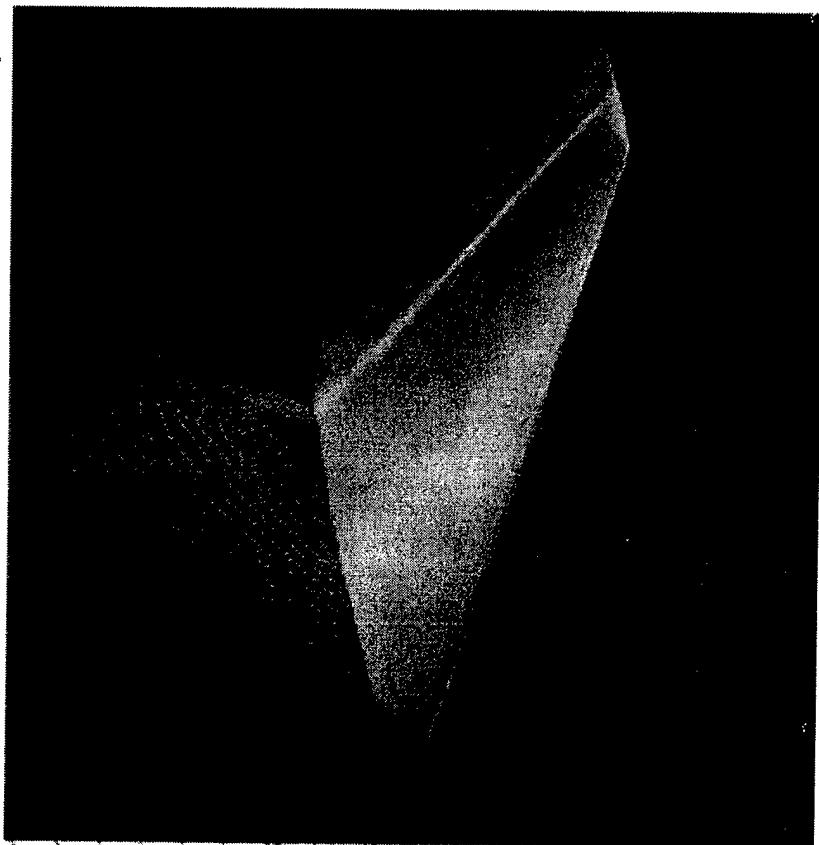
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F-16 HB/LCO Nonlinear Aeroelastic Model Computational Mesh and Steady Flow Solution

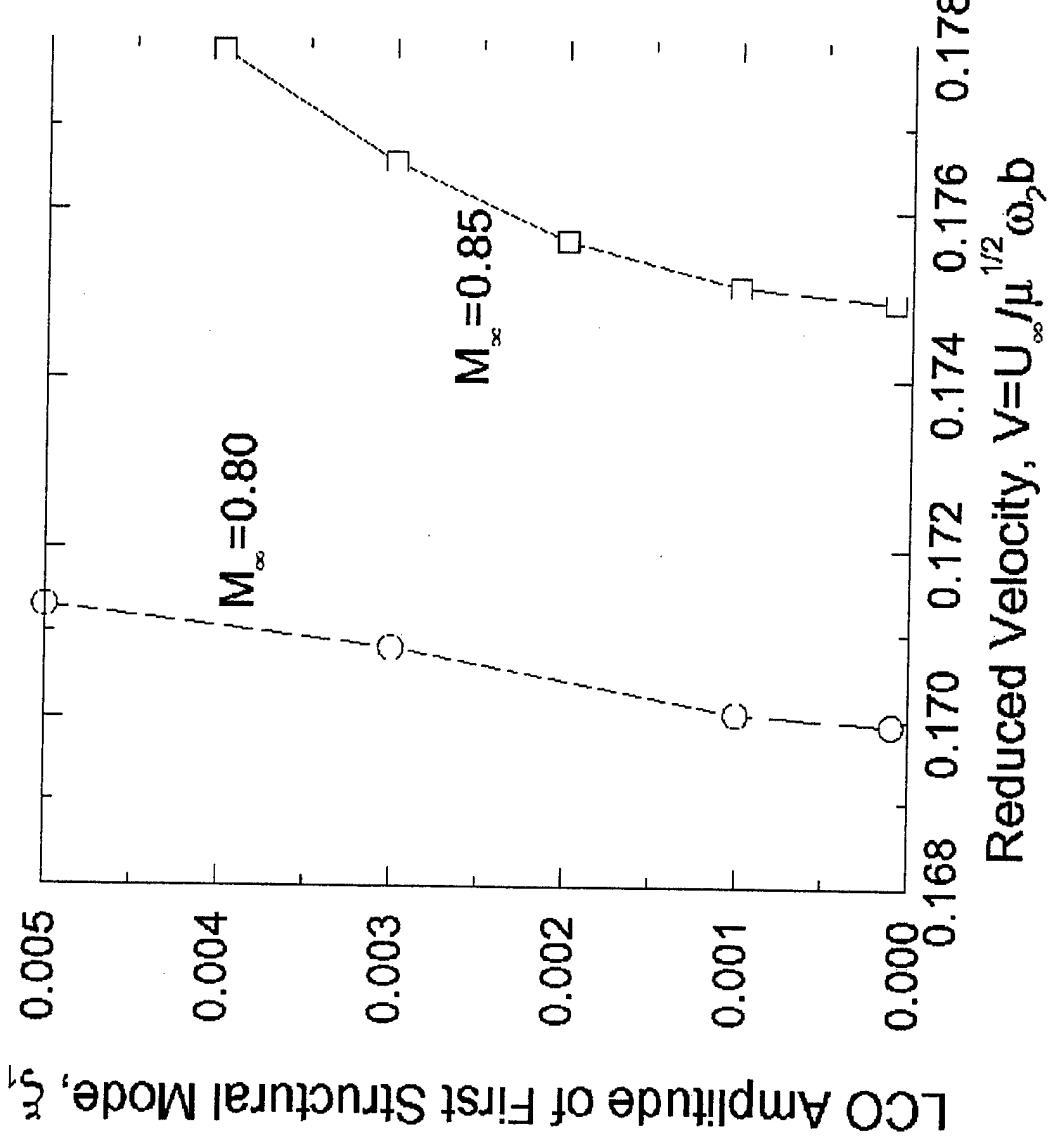
Computational Mesh



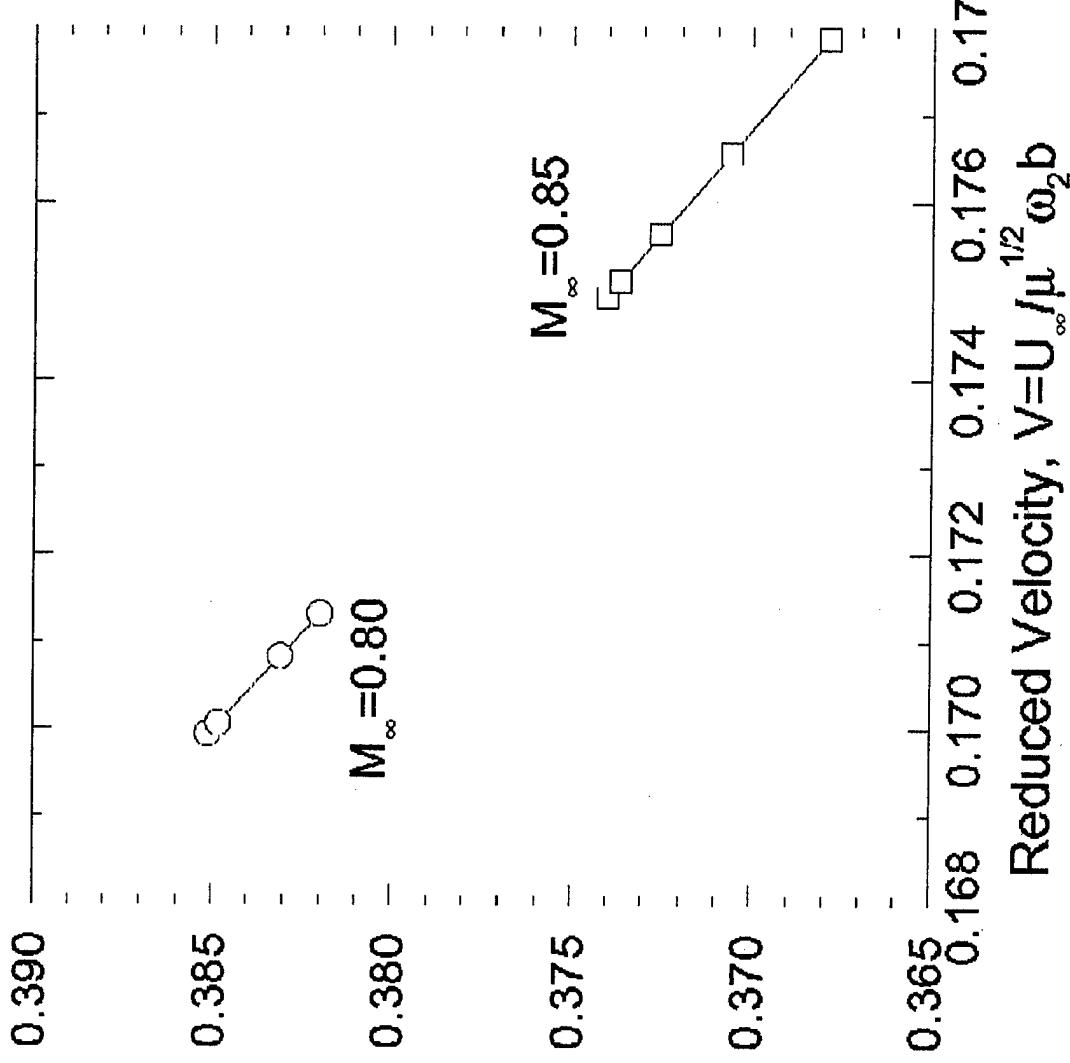
Mach Contours ($M_\infty = 0.9, \alpha = 1.0^\circ$)



F-16 Inviscid LCO Amplitude Response Trend $h=5,000$ feet, "Typical LCO" Structural Modes

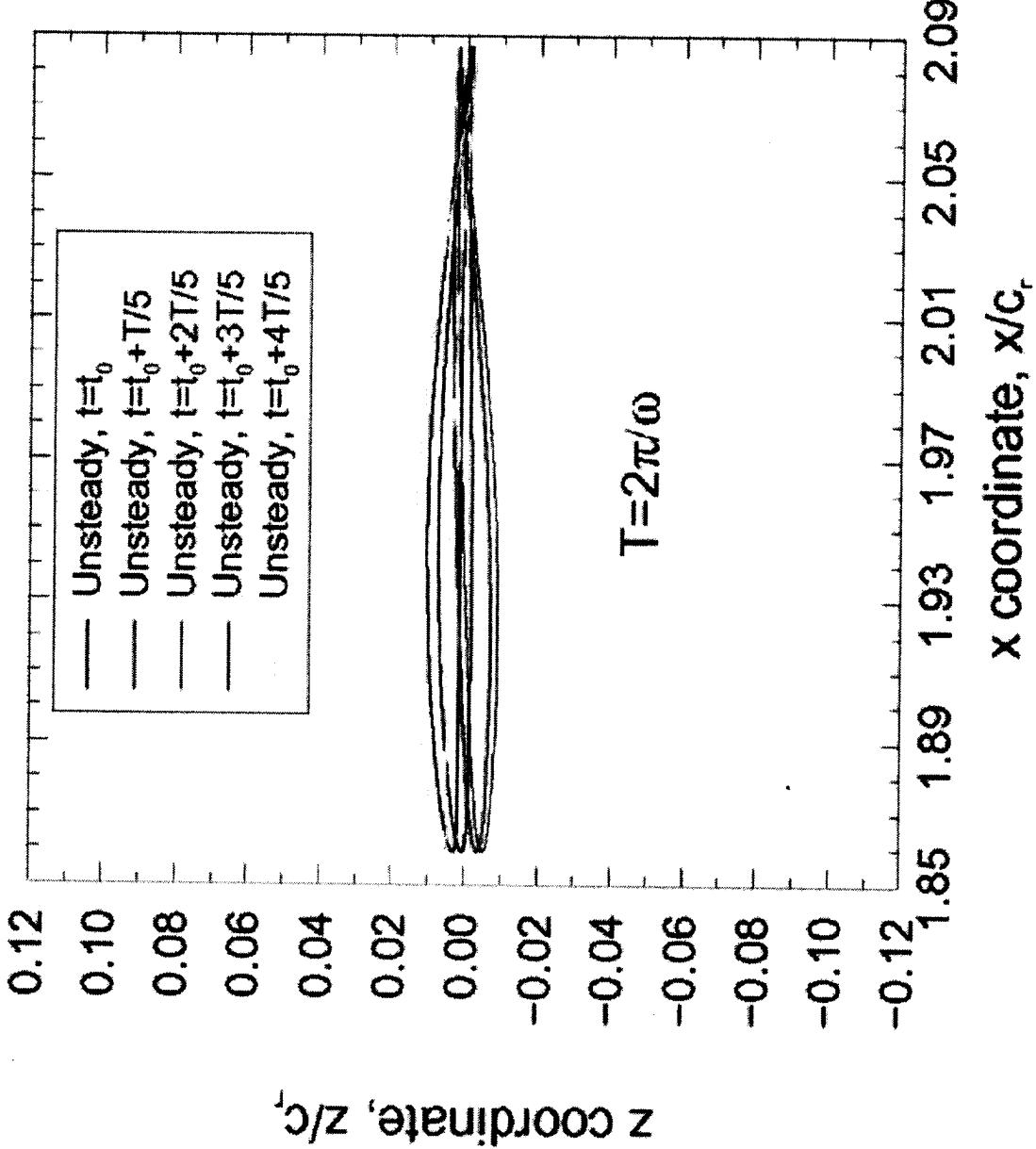


F-16 Inviscid LCO Frequency Response Trend $h=5,000$ feet, "Typical LCO" Structural Modes

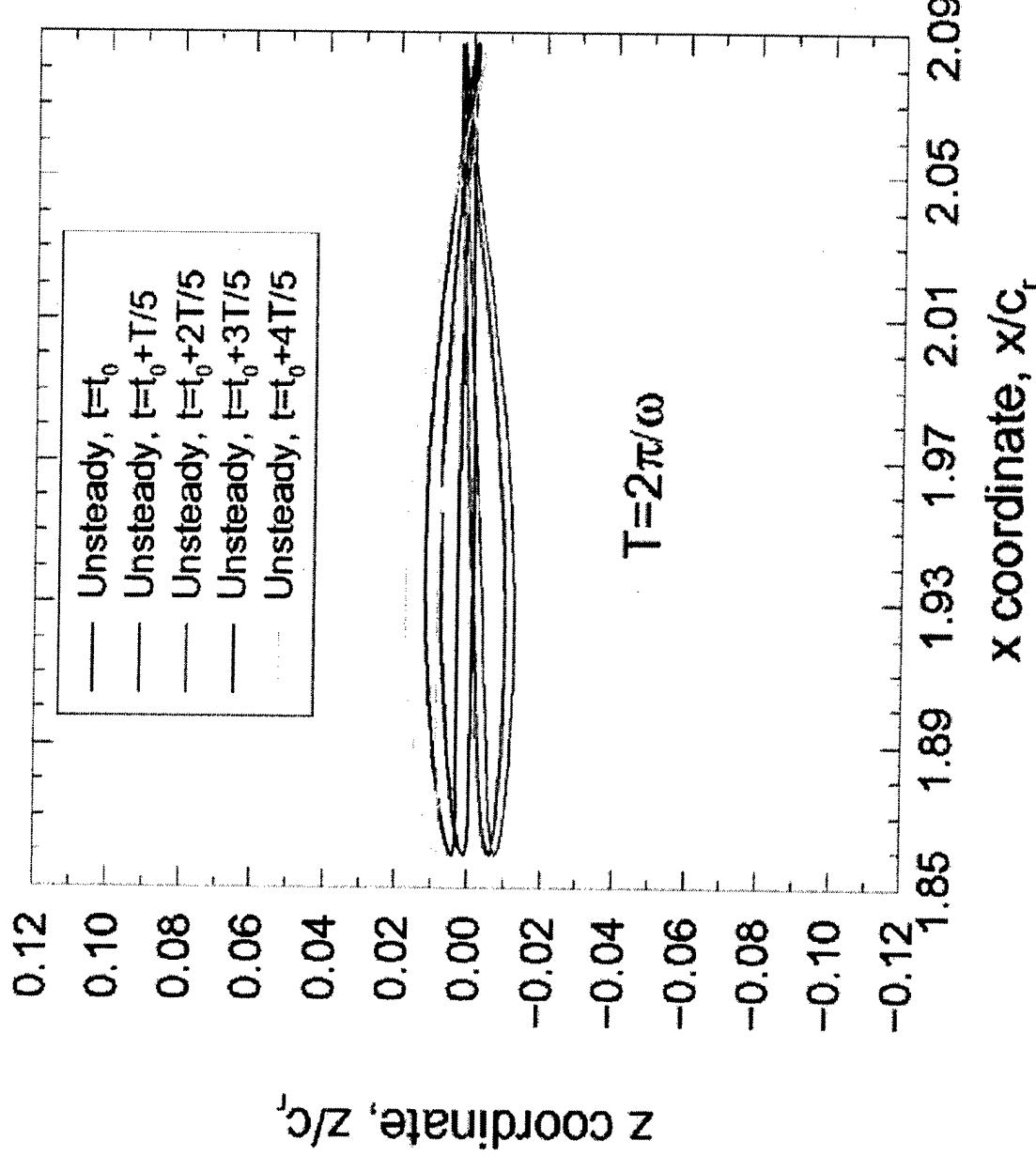


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F-16 Inviscid LCO Wing Tip Motion $\xi_1 = 0.004$ $M=0.85, h=5,000$ feet, "Typical LCO" Structural Mode Shapes



F-16 Inviscid LCO Wing Tip Motion $\xi_1 = 0.005$ $M=0.80, h=5,000$ feet, "Typical LCO" Structural Mode Shapes



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CONCLUSIONS

- VISCOSUS EFFECTS ARE IMPORTANT FOR SUPERCRITICAL AIRFOIL (NLR7301)
- BUT, LCO RESULTS FOR A CONVENTIONAL AIRFOIL (NACA 64A010) SHOW A MUCH SMALLER VISCOSUS FLOW EFFECT
- AN EULER (INVISCID) BASED LCO CAPABILITY NOW EXISTS FOR THREE-DIMENSIONAL FLOWS OVER WINGS USING POD/ROM AND HB
- WORK IS UNDERWAY TO EXTEND VISCOUS MODEL TO THREE-DIMENSIONAL FLOW FIELDS
- WIND TUNNEL AND FLIGHT TEST DATA ARE AVAILABLE FOR CORRELATIONS IN THREE-DIMENSIONAL FLOWS / FOCUS OF FUTURE WORK